Experimental Study on the Mechanism of Cathodic Protection Against Cavitation Erosion(キャビテーション壊食の陰極防御機構に関する実験的研究)

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論文内容要旨

Chapter 1 Introduction

Cavitation and cavitation erosion, which may be the most unpleasant hydrodynamic phenomena, occur in hydraulic machineries and devices, such as hydraulic turbines, pumps, hydrofoils, ship propellers, etc., and cause severe noise, vibration and damage. Recently, with development of science and technology, a rather higher speed is needed for these machineries and devices, so they are more often exposed to severe cavitation erosion. Growing interests have been therefore focused on finding a practical method to predict and prevent it to the utmost extend.

The cathodic protection, as one method to prevent or to mitigate cavitation erosion, has been investigated by some researchers. On their investigations, all of them found the same tendency that the mass loss caused by cavitation erosion decreased with increasing cathodic current, and came to a conclusion that such a decrease was mainly due to the cushion effect of the hydrogen gas evolved on the specimen surface. However, these studies were only limited to the measurment of the mass loss from specimen surface. there are few detailed studies on this method, and some basic problems have not been well understood yet. For examples, how do the cavitation nuclei, gas content rate of test solution and cavitation aspects change with the hydrogen gas bubbles evolved on the specimen surface? Are there macro and micro differences on eroded specimen surface with and without cathodic current? What is the reason that the cavitation erosion decreases as the cathodic current becomes larger?

In this dissertation, for the first step investigating the effect of the cathodic protection on the cavitation erosion, a series of experiments is conducted to give some information on these questions mentioned above, especially on the mechanism of cathodic protection against cavitation erosion.

Chapter 2 Cavitation Nuclei Size Distributions Under the Condition of Cathodic Protection

The cavitation erosion experiments are carried out by using an electrostrictive vibratory apparatus as shown in Fig. 1. The driving frequency " f " of the vibratory generator is 19.5kHz, the double amplitude " a " (peak to peak) is kept at 50μm conforming to the ASTM Standard, and the driving power is 1200W. A 3 percent (in weight) solution of sulfate sodium (Na_2SO_4) in distilled water is used as the test liquid. The test liquid temperature is controlled within 22±1 ℃ by means of a cooler. The stationary specimen is placed in close proximity and parallel to the vibrating disk. The cathode is the stationary specimen and the anode is made of platinum. The cathodic current between two electrodes is held constant during test run by a regulated DC power supply.

In cavitation erosion experiments, the basic experimental conditions such as cavitation nuclei and gas content should be determined. Under the condition of the cathodic protection, since the specimen is made as a cathode and the hydrogen gas will be evolved on the specimen surface, it can be thought that the cavitation nuclei and gas content of test solution maybe change with these free hydrogen gas bubbles to some extent and it is necessary to clarify this problem. Therefore, in this chapter, for the first step of this study, the behaviors of the cavitation nuclei and gas content in test solution with test time and cathodic current are measured by a Coulter counter and a van Slyke apparatus, respectively. And the cavitation aspects are photographed with a xenon flash lamp of 1 μs exposure time.

It is found that the cavitation nuclei distribution varies with test time t and increases with cathodic current I. Some large size nuclei (40μm~55μm) occur when the hydrogen gas is evolved on the specimen surface. It is also found that the gas content increases with I resulting from a small part of hydrogen gas remained in the test solution, and its amount is approximately estimated. Although the cavitation aspects scarcely change with t, they are affected by I, and the size and number of cavitation bubbles increase as cathodic current becomes larger. The increase of nuclei and the occurrence of large size nuclei corresponding to the hydrogen gas are maybe responsible for the change of cavitation aspects.

Chapter 3 Effects of Cathodic Protection on Cavitation Erosion

In this chapter, the cavitation erosion tests are carried out on a soft material made of copper and an erosion-resistant one made of SUS304. The mass loss, the surface roughness and the erosion patterns with respect to test time t and cathodic current I are carefully measured and observed by a digital balance, a profilometer and a scanning electron microscope (SEM). It is found that the mass loss, the mass loss rate and the surface roughness caused by the cavitation erosion decrease with increasing cathodic current, especially at the range of $I \leq 0.5A$ for both kinds of specimens. It is confirmed again that the cathodic current or the hydrogen gas evolved on the specimen surface has a real protection effect against the cavitation erosion. And such protection is more effective on a high erosion-resistant SUS304 material than on a low erosion-resistant copper(see Fig. 2). It should be noted that although the specimen is almost prevented from cavitation erosion when the cathodic current increases up to 1.0A, there exists an optimum value for I used in the cathodic protection, which should be determined by the practical conditions.

Chapter 4 SEM Observation of Erosion Patterns

In order to clarify the effects of the cathodic protection on the cavitation erosion, the erosion patterns are carefully observed with respect to test time t and cathodic current I by means of a SEM and are shown in Fig. 3.

It is found that for the copper specimen under the condition without I, the cavitation erosion is mainly due to the extremely large plastic deformation leading to the formation and coalescence of cracks and particle fall-off on a large scale caused by collapse pressure of the cavitation bubbles. It can be said that this is a typical ductile-fracture mechanism. Moreover, it is worth noting that the cathodic current does not affect the erosion mechanism (ductile-fracture) from the microscopic view. But the erosion developing speed from the plastic deformation in the incubation period to the particle fall-off in the acceleration and steady state period are markedly suppressed by I. From the microscopic observasion, it is known that the erosion is not uniform on the specimen surface. It is more intense at the grain boundaries than that in the grain especially in the incubation period.

Chapter 5 Characteristics of Cavitation Noise and Vibration

In this chapter, the cavitation noise and cavitation-induced vibration are measured and analyzed under the condition of the cathodic protection. The correlations of cavitation erosion, noise and vibration are examined. And the mechanism of the cathodic protection is also examined from these characteristics. It is found that the power spectrum and sound pressure level of cavitation noise markedly decrease with increasing cathodic current I, especially those in the ultrasonic region, which are directly produced by cavitation bubble collapses. And the large pulses of cavitation noise corresponding to the high pressure impulses caused by cavitation also considerably decrease with increasing I, which may indicates why cavitation erosion is markedly reduced under the condition of cathodic protection. The vibratory acceleration also shows a similar behavior to cavitation noise. Moreover, the mass loss rate in the steady state period is found to be linearly related to cavitation energy in the ultrasonic region and vibratory acceleration. Thus, it can be said that the cavitation noise and vibratory accelerarion can be used as the monitoring factors of cavitation erosion, even under the condition of cathodic protection. The decrease of cavitation noise and vibration gives a support that the hydrogen gas bubbles can absorb the cavitation energy, resulting in the decrease of mass loss caused by cavitation and protecting the specimen surface from cavitation erosion.

Chapter 6 High-Speed Photographic Observations of Cavitation Aspects

In this chapter, the cavitation aspects are photographed and observed by means of a xenon flash lamp of $1 \mu s$ exposure time and a high speed motion analyzer, and the effects of noncondensable gas on the cavitation bubble collapse are examined from the viewpoint of the bubble dynamics.

It is clarified that the cathodic protection mechanism of cavitation erosion, the so-called cushion effect, can be divided into three parts. The first one is the effect of hydrogen gas inside cavitation bubble, by which the maximum collapse velocity and pressure of the cavitation bubble will be markedly decreased with increasing the noncondensable gas pressure inside it. The second one is the effect of hydrogen gas bubbles attached on the surface of the cavitation bubble, which affects the collapse process of cavitation bubble and makes the cavitation bubble collapse more slowly and gently. The third one is the effect of hydrogen gas bubbles distributed widely outside cavitation bubble, that is, in the test liquid. These hydrogen gas bubbles make the compressibility of test liquid high and the sonic velocity low, resulting in the further decrease and attenuation of the impulsive pressure caused by cavitation bubbles in its propagation process. The combination of these three kinds of effects can be considered as the exact meaning of cushion effect. As a result, the cavitation erosion is considerably reduced.

Chapter 7 Cavitation-Induced Pressure

In this chapter, the impulsive pressure caused by cavitation bubble collapses is measured by using the sensitive-pressure film method, and the cavitation aspects on the horn tip surface with cathodic current I are observed. The mechanism of cathodic protection is also examined from this viewpoint. It is found that the impulsive pressure caused by the cavitation bubble collapses, that is, a direct cause of the cavitation erosion markedly decreases with increasing I, especially at the peripheral region of specimen surface. From this fact, the decrease of the cavitation erosion with increasing I can be easily understood. On the basis of the cavitation aspect observations, it is indicated that the shock rings becomes smaller with increasing I, suggesting that the shock pressure caused by some large bubble collapses decreases with increasing I. Such decrease implies that hydrogen gas can absorb part of the cavitation energy, and attenuate the shock pressure.

Chapter 8 Characteristics of Sonoluminescence Under Cathodic Protection Condition

In order to clarify the mechanism of cathodic protection against cavitation erosion, the sonoluminescence as one aspect accompanied by cavitation with cathodic current I is measured in both 3%Na_2SO_4 and 3%H_2SO_4 solutions. And its aspects are photographed by an image intensifier.

It is found that the relative intensity of sonoluminescence increases as cathodic current becomes larger(see Fig. 3), namely, the cavitation accompanied by the electrolytic reaction can make the sonoluminescence intense. Such enhancement is due to two factors. The first factor that can be considered is the hydrogen gas bubbles evolved on the horn tip surface. Another factor to be considered is the sodium ion Na^+. It is clarified that the hydrogen gas bubbles mainly contribute to the sonoluminescence in the region of short wavelength (λ <460nm) and are responsible for the increase of spectra in this region. While Na^+ mainly contributes to the sonoluminescence of λ >460nm and is responsible for the increase in this region. Therefore, it is confirmed that the hydrogen gas bubbles evolved on the horn tip surface can partially absorb the energy of cavitation bubble collapse and also give out sonoluminescence like cavitation bubbles.

Chapter 9 Conclusions

In this chapter, the main conclusions in this study are summarized.

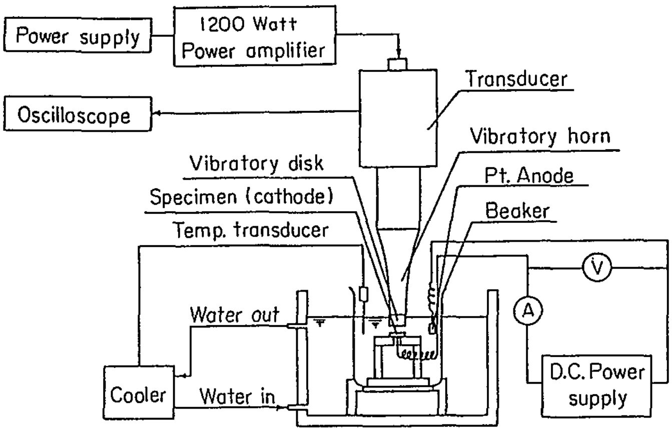

Fig. 1 Schematic diagram of test apparatus

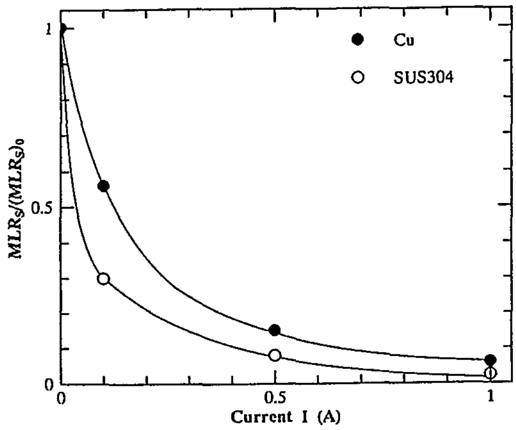

Fig. 2 Mass loss rate in steady state period versus I

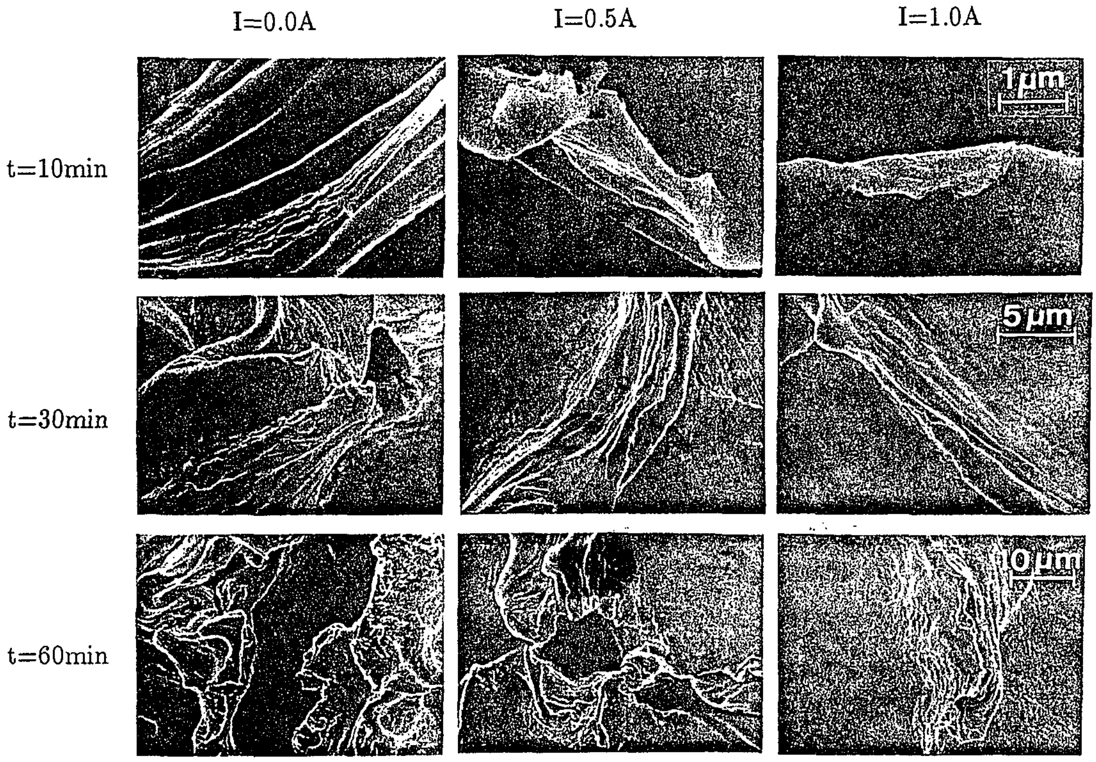

Fig. 3 SEM photographs on eroded specimen surface

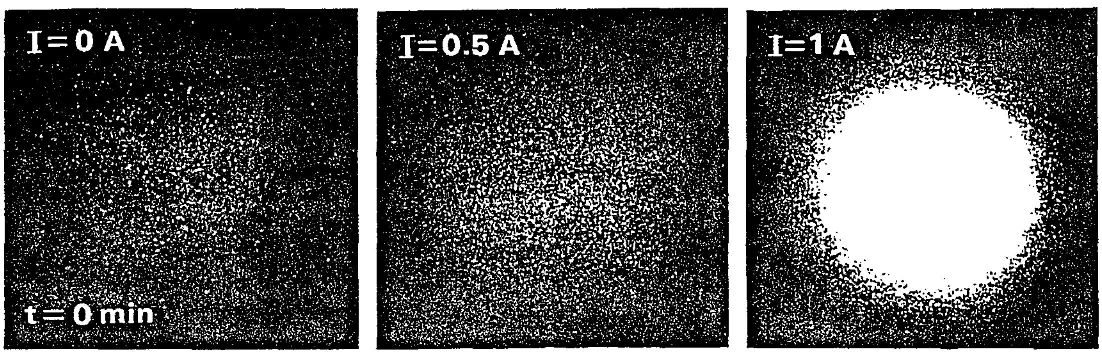

Fig. 4 Aspects of sonoluminescence

審査結果の要旨

流体機械・機器の高速化・高性能化に伴い、これらの寿命を左右するキャビテーション損傷の問題は安全設計上工学的に重要な課題である。本論文は、機械に致命的な損傷を与えるキャビテーション壊食を大幅に軽減させる陰極防御法の確立をめざして、その防御機構を明らかにしたもので、全編9章よりなる。

第1章は序論である。

第2章では、キャビテーション壊食試験法として用いた間接式振動試験装置において、重要な影響因子となる試料水溶液中のキャビテーション核、水素ガス含有量の経時変化を印加陰極電流に対して明らかにしている。

第3章では、振動試験より質量欠損、表面粗さ、壊食パターンを測定し、陰極電流によって著しい陰極防御効果が現れることを定量的に明らかにしている。

第4章では、走査電子顕微鏡を用いて材料壊食面を微視的に観察している。陰極電流の印加により、壊食発達過程の進行速度が大幅に抑制され、非凝縮性水素ガスのクッション効果が顕著であることを述べている。これは、重要な知見である。

第5章では、騒音と振動加速度の音響・振動エネルギーの水素ガス気泡による吸収効果が顕著となること、これらのエネルギーと質量欠損率との間に線形関係があることを見い出している。これらの知見は、壊食のモニタリングの視点からも興味深い。

第6章では、高速ビデオを用いてキャビテーションの様相を詳細に観測し、クッション効果は、キャビテーション気泡の近傍に微細水素ガス気泡が集積することにより崩壊圧を緩和する効果、液中に広く分散している水素ガス気泡による衝撃波の減衰効果、水素ガスの拡散によってキャビテーション気泡内圧を増加させその崩壊を直接緩和する効果に分類されることを明示している。これらは、陰極防御機構を考える上で、非常に重要な知見である。

第7章では、試験片表面の衝撃圧力分布を感圧紙によって直接測定し、陰極電流により衝撃圧が著しく低減することを定量的に示している。

第8章では、音響ルミネッセンスを分光学的に解析することにより、波長400nm付近の発光ピークはキャビテーション壊食エネルギーの吸収によって生じていることを明らかにしている。これは陰極防御効果の別の証拠であり、注目される。

第9章は結論である。

以上要するに本論文は、流体機械の高速化に伴って生ずるキャビテーション損傷を防止する上で有効な陰極防御効果を解明し、その防御機構を明確にしたもので、機械工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。